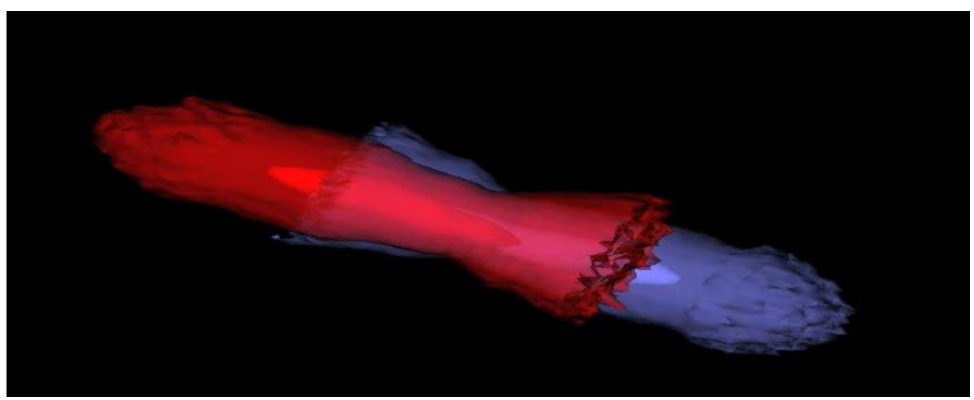
Fully 3-D multiple beam dynamics processes simulation of the Fermilab Tevatron:

A SciDAC Breakthrough

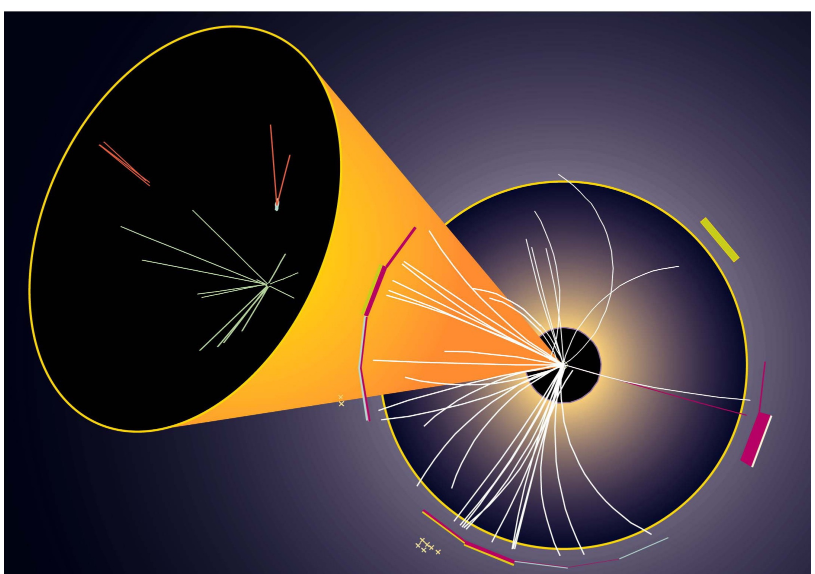
E. Stern, J. Amundson, P. Spentzouris and A. Valishev

Fermi National Accelerator Laboratory



The Big Questions: time, space, matter and energy

Cosmology and Astrophysics
Observing the stars



High Energy Particle Physics

Running experiments at accelerators

Finding new phenomena

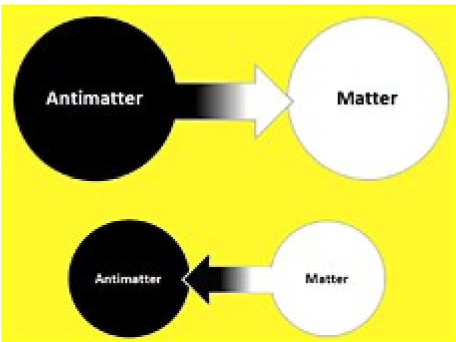
The Fermilab Tevatron

Colliding protons and antiprotons at 1 TeV, the highest energy accelerator in the world up until March 2010!

Recent results from the Tevatron program

Submitted to Phys. Rev. D

Fermilab-Pub-10/114-E



Evidence for an anomalous like-sign dimuon charge asymmetry

V.M. Abazov,[36] B. Abbott,[74] M. Abolins,[63] B.S. Acharya,[29] M. Adams,[49] T. Adams,[47] E. Aguilo,[6] G.D. Alexeev,[36] G. Alkhazov,[40] A. Alton[a],[62] G. Alverson,[61] G.A. Alves,[2] L.S. Ancu,[35] M. Aoki,[48] Y. Arnoud,[14] M. Arov,[58] A. Askew,[47] B. Åsman,[41] O. Atramentov,[66] C. Avila,[8] J. BackusMayes,[81] F. Badaud,[13] L. Bagby,[48] B. Baldin,[48]

Phys. Rev. Lett. 104, 2010

Combination of Tevatron searches for the standard model Higgs boson in the W^+W^- decay mode

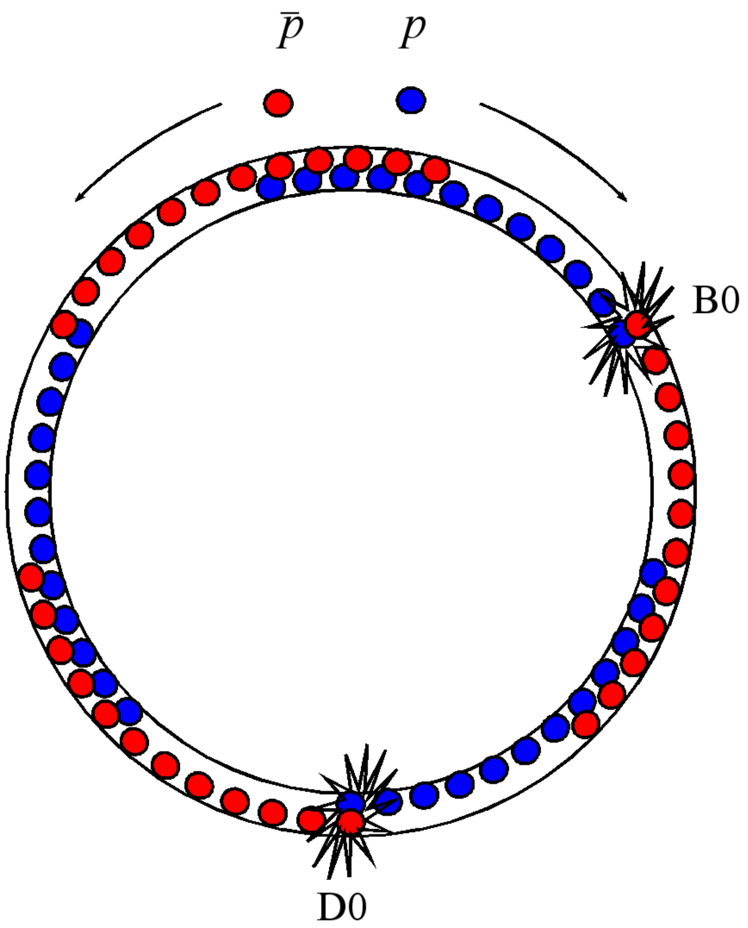
T. Aaltonen[†,15] V.M. Abazov[‡,53] B. Abbott[‡,121] M. Abolins[‡,106] B.S. Acharya[‡,35] M. Adams[‡,84] T. Adams[‡,80] J. Adelman[†,83] E. Aguilo[‡,7] G.D. Alexeev[‡,53] G. Alkhazov[‡,57] A. Alton[mm‡,104] B. Álvarez González[z†,61] G. Alverson[‡,99] G.A. Alves[‡,2] S. Amerio[ff†,39] D. Amidei[†,104] A. Anastassov[†,86] L.S. Ancu[‡,52] A. Annovi[†,38] J. Antos[†,58] M. Aoki[‡,82] G. Apollinari[†,82] J. Appel[†,82] A. Apresyan[†,91] T. Arisawa[†,46] Y. Arnoud[‡,17] M. Arov[‡,95] A. Artikov[†,53] J. Asaadi[†,128] W. Ashmanskas[†,82] A. Askew[‡,80] B. Åsman[‡,62] O. Atramentov[‡,109] A. Attal[†,59] A. Aurisano[†,128] C. Avila[‡,10] F. Azfar[†,70] J. BackusMayes[‡,133] F. Badaud[‡,16] W. Badgett[†,82] L. Bagby[‡,82] B. Baldin[‡,82] D.V. Bandurin[‡,94] S. Banerjee[‡,35] A. Barbaro-Galtieri[†,72] E. Barberis[‡,99] A.-F. Barfuss[‡,18] P. Baringer[‡,93] V.E. Barnes[†,91] B.A. Barnett[†,96] J. Barreto[‡,2] P. Barria[hh†,40] J.F. Bartlett[‡,82] P. Bartos[†,58] U. Bassler[‡,21] D. Bauer[‡,67] G. Bauer[†,101] S. Beale[‡,7] A. Bean[‡,93] P.-H. Beauchemin[†,6] F. Bedeschi[†,40] D. Beecher[†,68] M. Begalli[‡,3] M. Begel[‡,117] S. Behari[†,96] C. Belanger-Champagne[‡,62] L. Bellantoni[‡,82] G. Bellettini[gg†,40] J. Bellinger[†,134] J.A. Benitez[‡,106] D. Benjamin[†,118] A. Beretvas[†,82] S.B. Beri[‡,33] G. Bernardi[‡,20]

High intensity beams in the Tevatron

Destabilizing effects

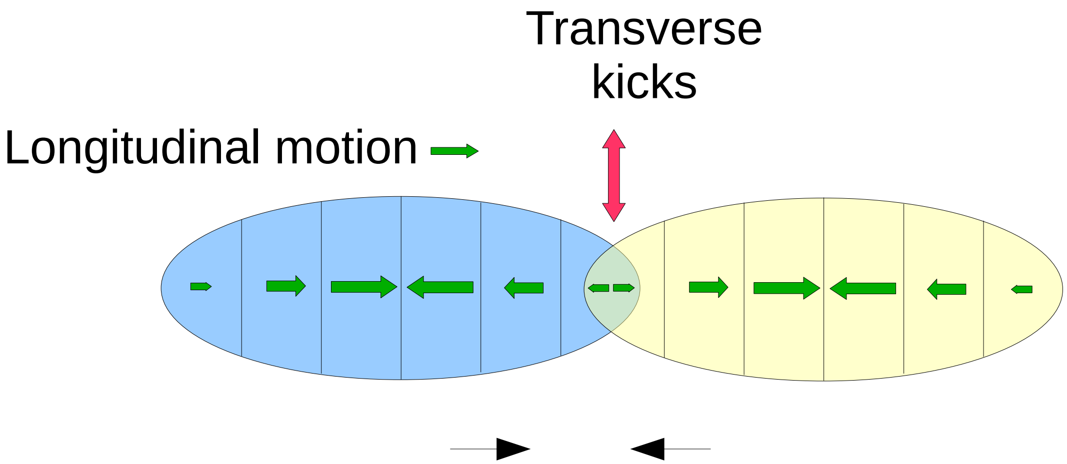
- Beam-Beam interactions
  - Bunch-bunch coupling
  - Head-tail coupling
- Machine impedance
  - Longitudinal-transverse coupling
- Chromaticity
  - excites instabilities

Schematic of Tevatron bunches in the ring



Numeric simulation is the only way to study the problem without disrupting operations

BeamBeam3d code



Parallel 3-D Poisson beam-beam force calculation*

Features developed for Tevatron simulation

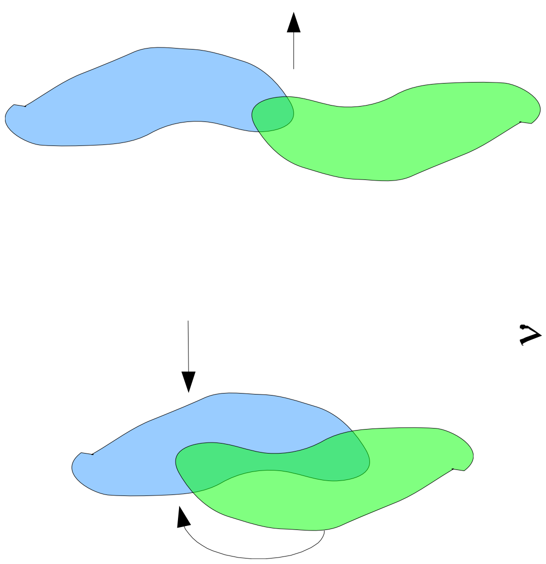
- Coupled XY maps
- Independent multi-bunch tracking
- Helical trajectory
- Full collision pattern
- Resistive wall impedance
- Chromaticity

Validate each beam dynamics process individually, either with measured data or with analytic calculations.

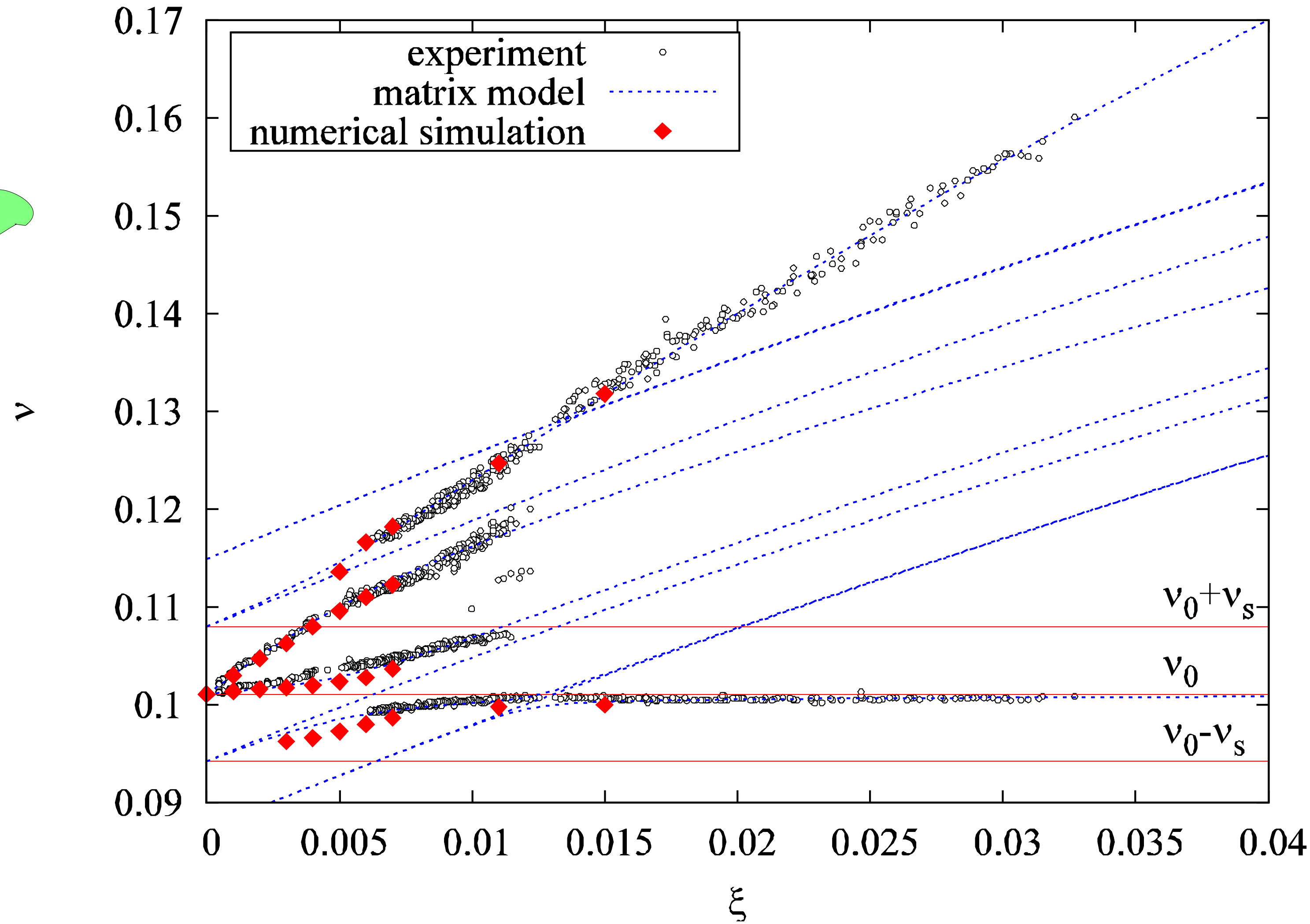
[*] J. Qiang, et al, J. Comp. Phys. 198 (2004)

Beam-beam validation

VEPP-2M 500 MeV e^+e^- collider synchro-betatron mode evolution measurement

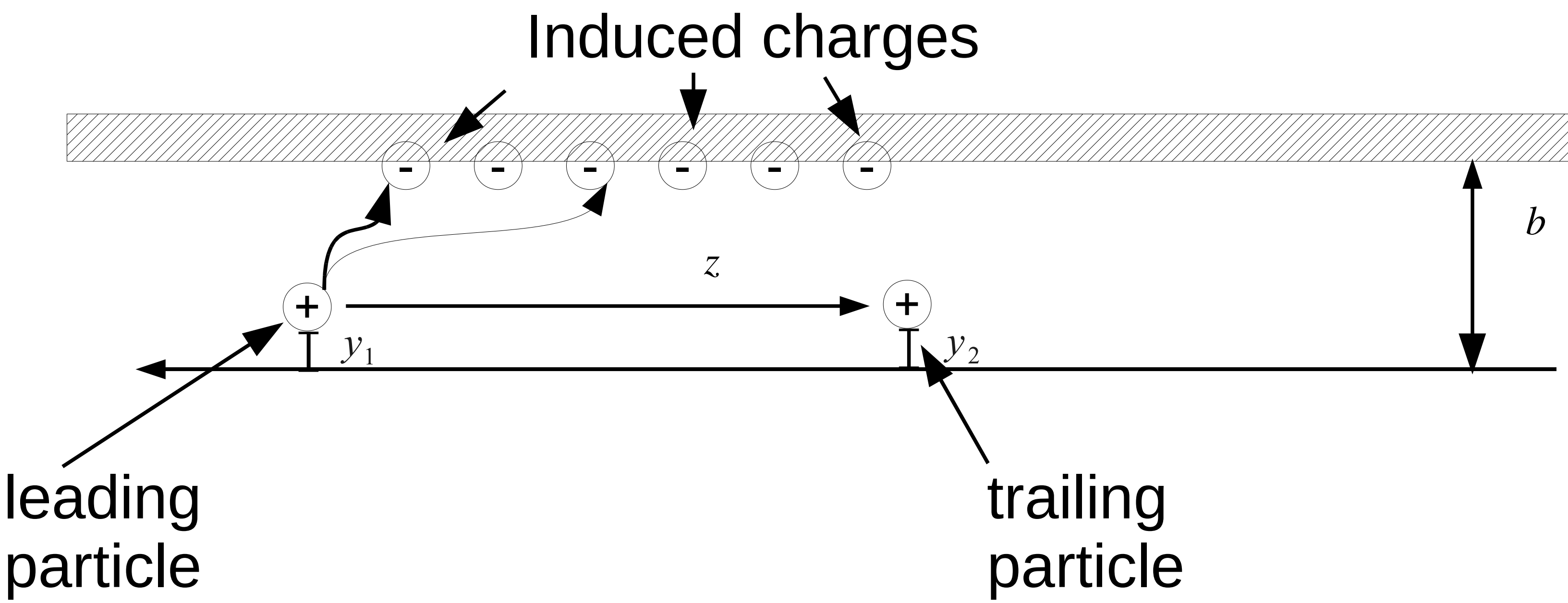


$$\xi = \frac{N_e r_e}{4\pi\gamma\epsilon}$$



*I.N.~Nesterenko, et al.Phys.Rev.E, 65, 056502 (2002)

Impedance model

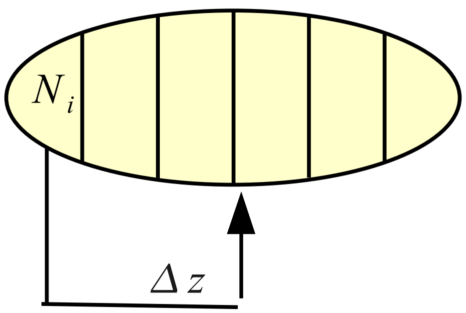


wake

$$W = \left(\frac{2}{\pi b^3}\right)\sqrt{\frac{4\pi\epsilon_0 c}{\sigma}}\frac{L}{\sqrt{\Delta z}}$$

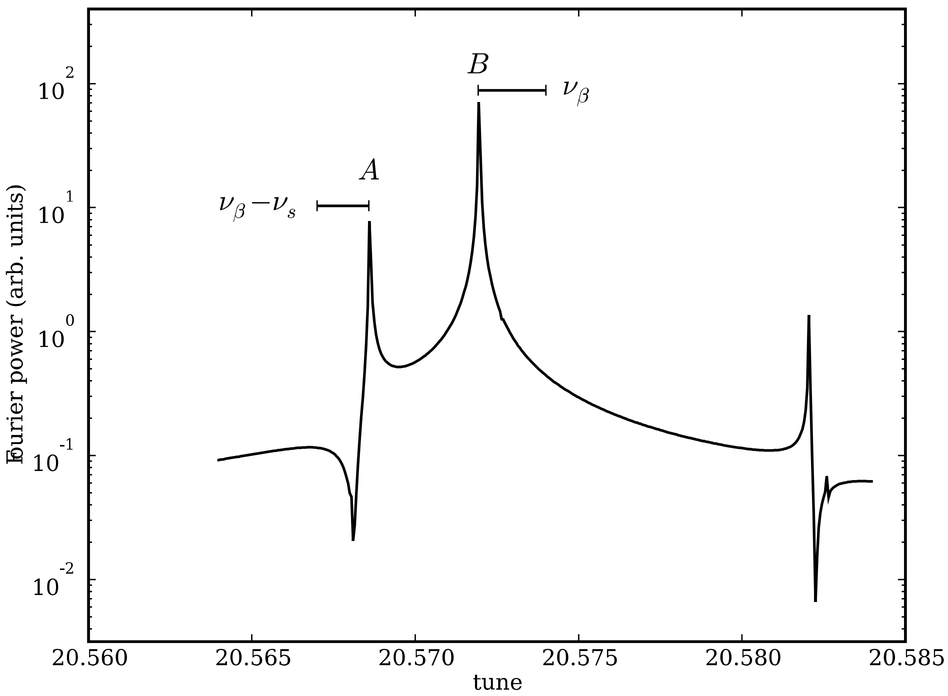
kick

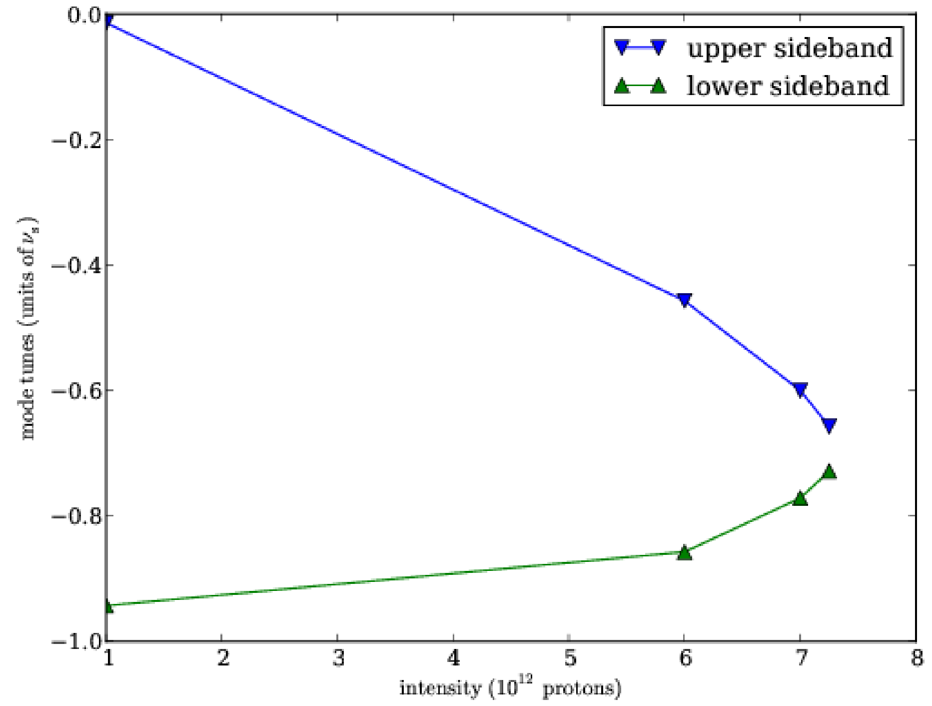
$$\Delta y_2' = \frac{N_i r_p}{\beta\gamma} W y_1$$



Impedance validation (1): tune splitting evolution

Well understood variation of tune split with beam intensity





Sidebands meet at expected location

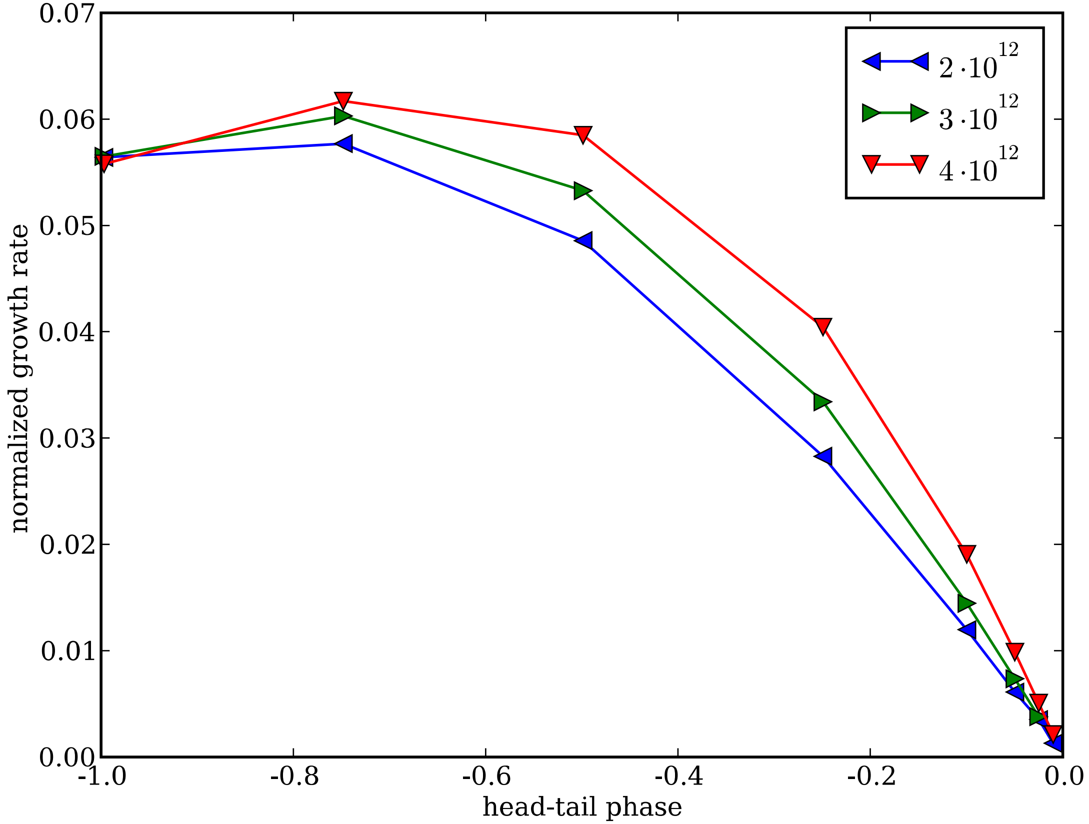
Impedance validation (2): instability growth rates

head-tail phase

$$\chi = \frac{\xi \omega_\beta \hat{z}}{c \eta}$$

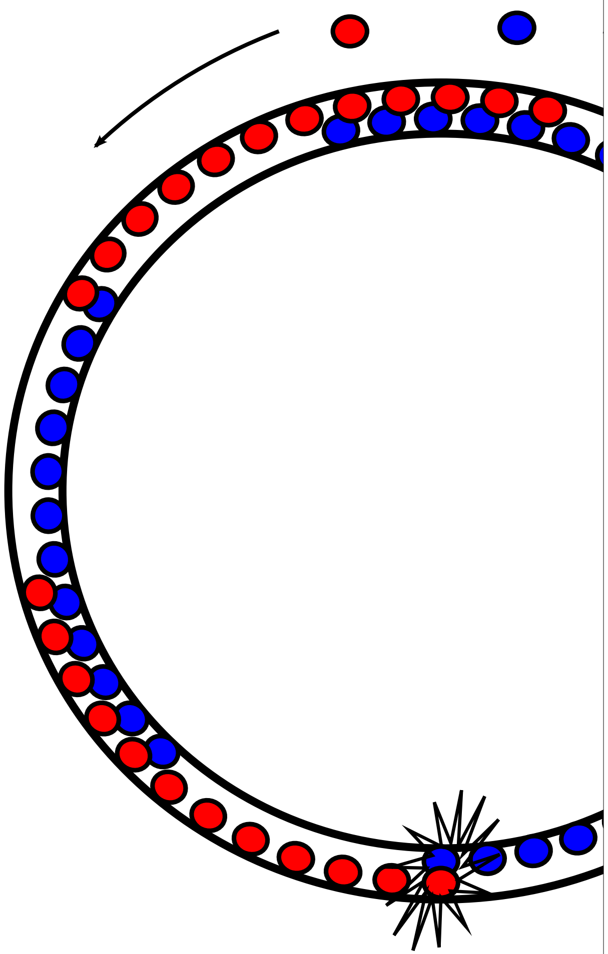
instability growth rate

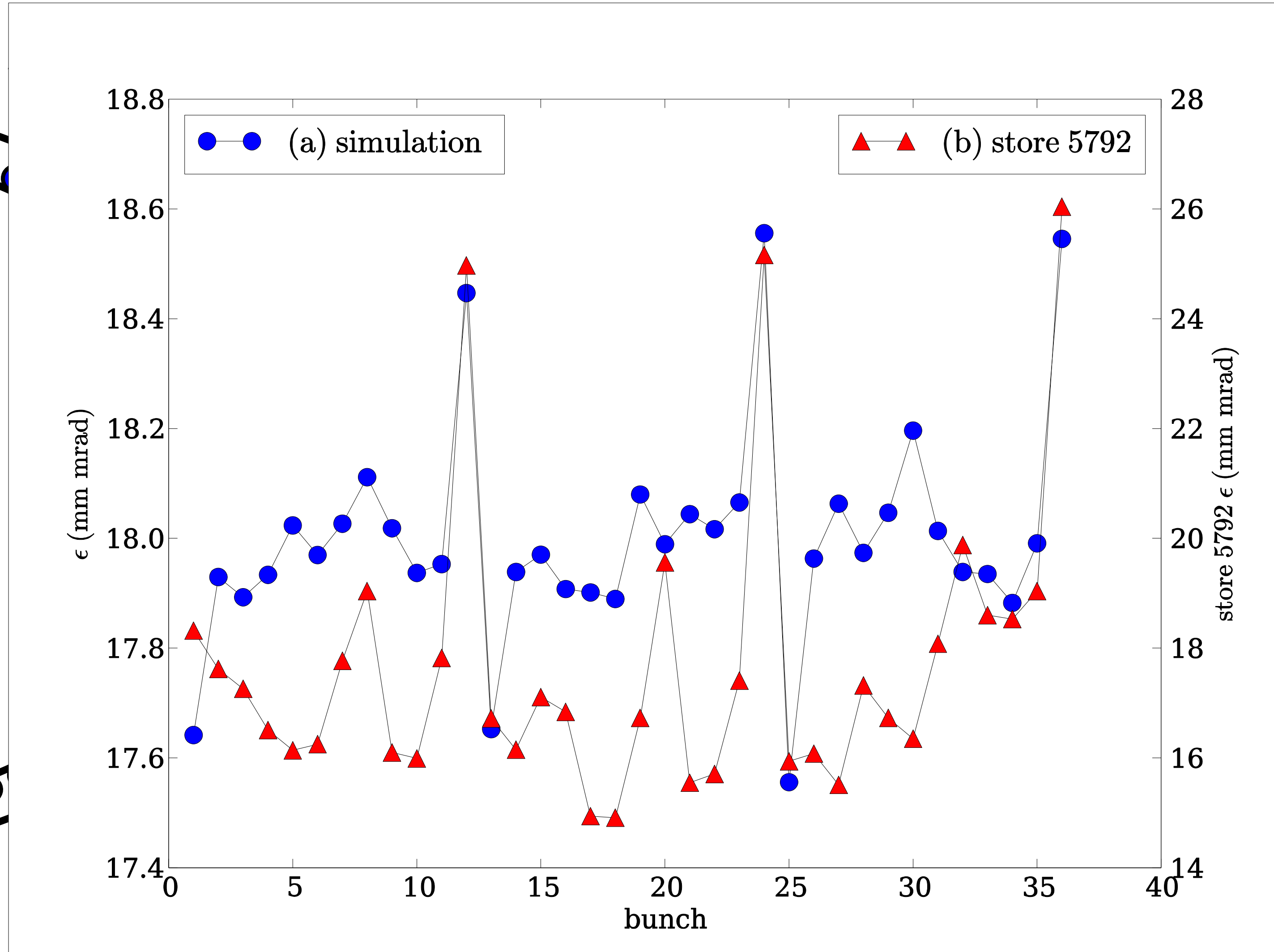
$$\tau^{-1} = \frac{N r_o W_0}{2 \pi \beta \gamma \nu_\beta} \chi$$



impedance model validated

Bunch dependent emittance growth





Pattern reproduced by the simulation

Tevatron setup dance

The Tevatron is unstable at high intensities

Adding chromaticity can improve stability

Chromaticity causes losses and radiation

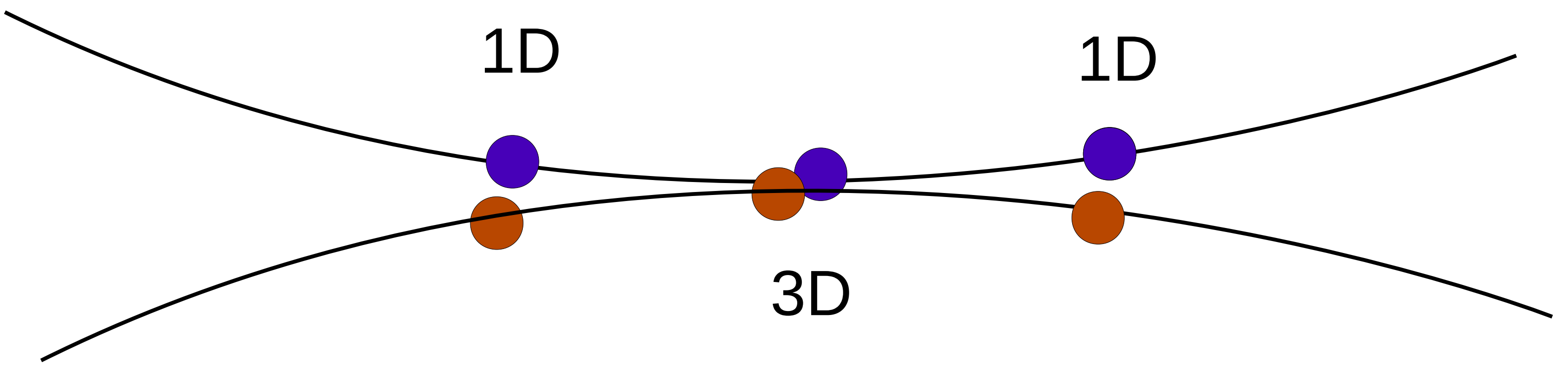
Beam-beam force is stabilizing

During setup, beam-beam force is reduced

But is it enough to give beam stability?

Computation

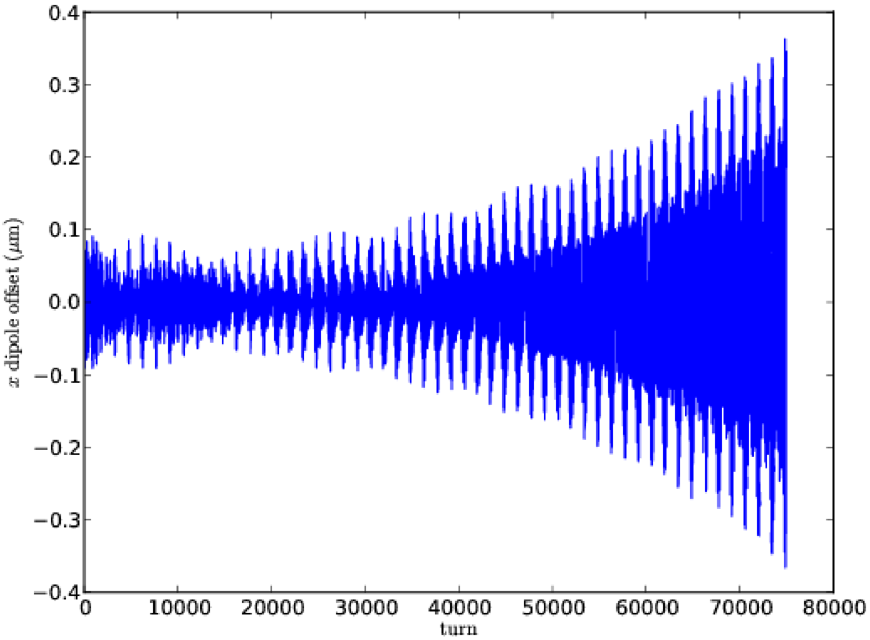
- Jobs run on ~1000 cores on BG/P
- Full 3D interactions very slowly



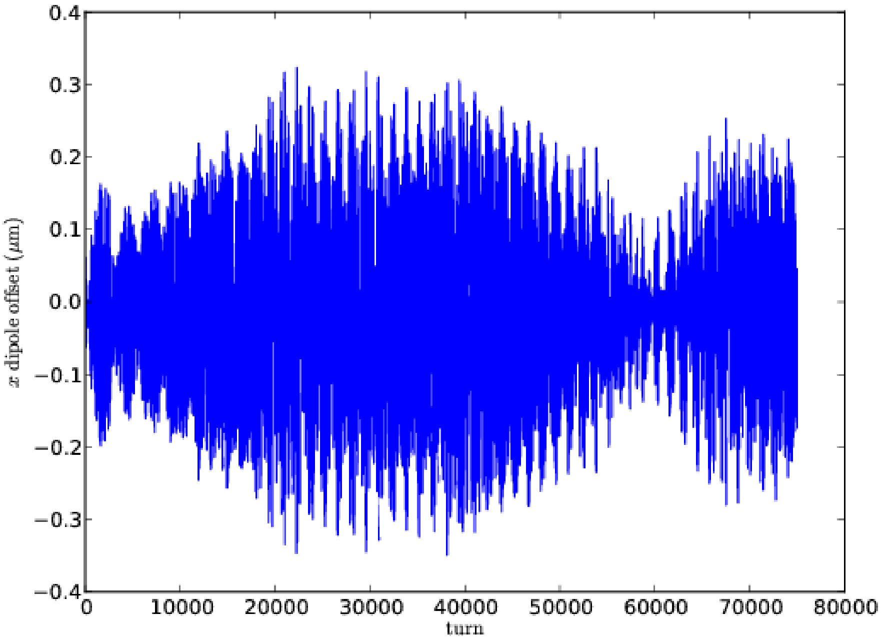
- Simplified problem runs ~1500 turn/hour
- Real accelerator: 48K turns/second
- ~250 jobs for this investigation (production&validation)
- 5 million core hours on Intrepid BG/P

Weak beam-beam stability studies

No beam-beam



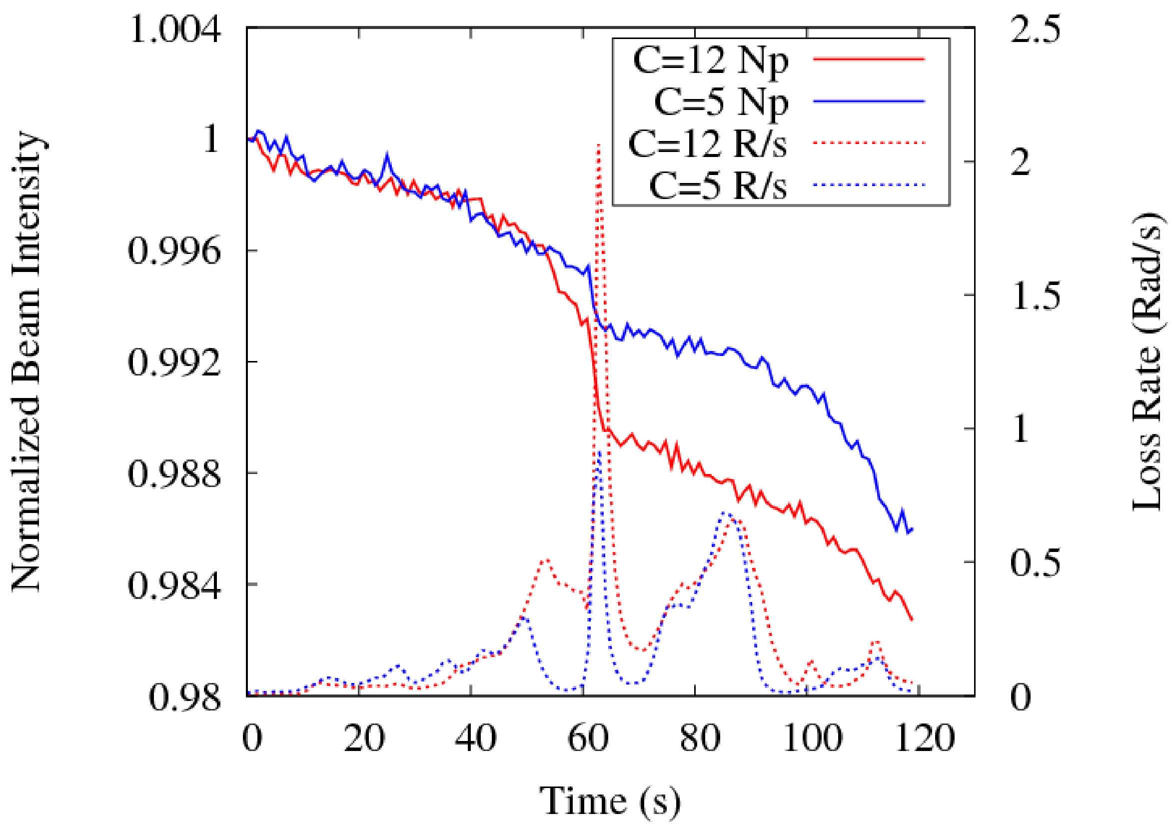
Weak beam-beam



Lowered chromaticity works!

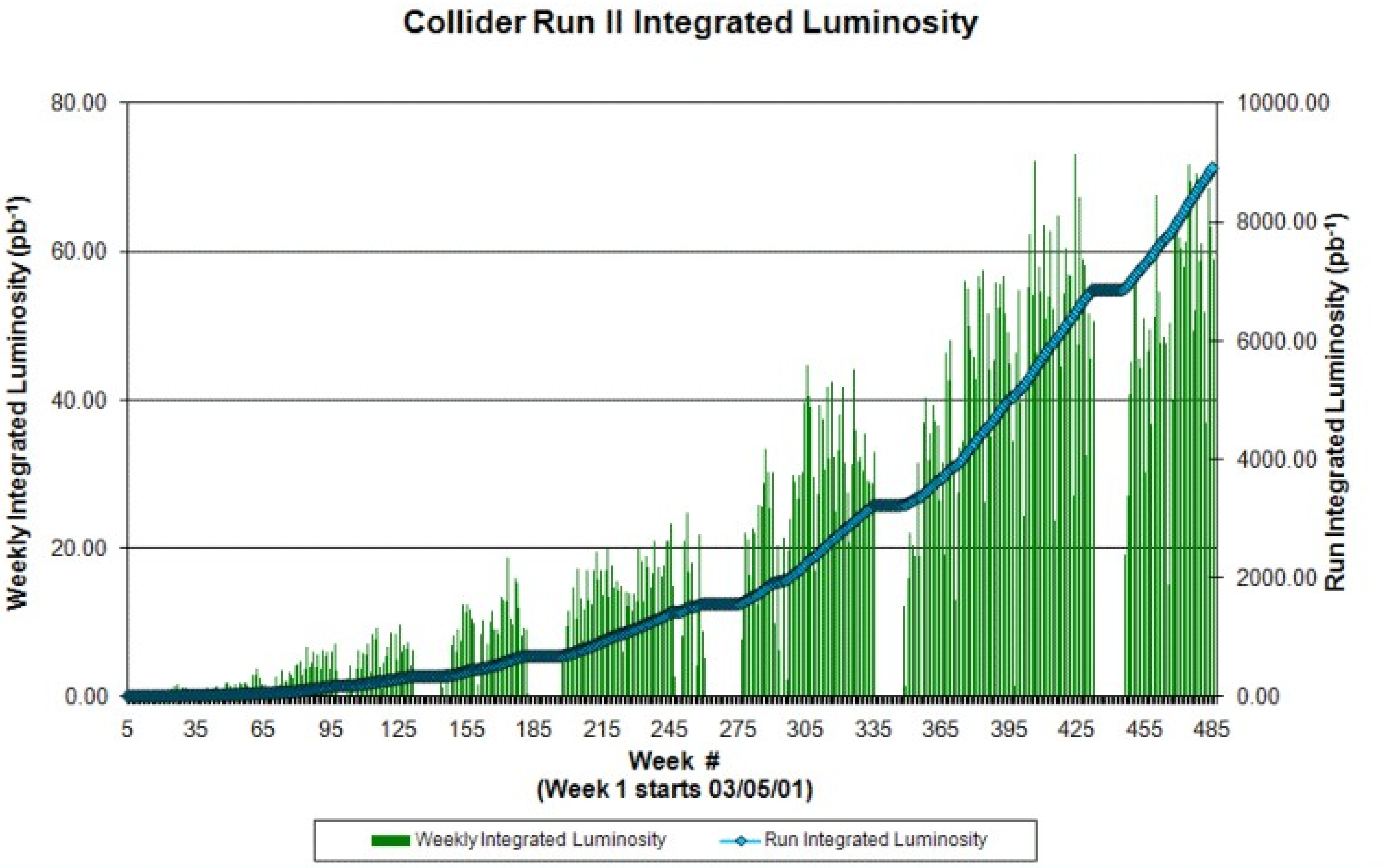
A. Valishev
PAC2009, Recent Tevatron Operational Experience

Normalized Proton Loss During Low-Beta Squeeze



Red traces – before chromaticity change at sequence 14, blue - after

Contributes to data collection improvement



Summary

- We have developed an comprehensive multiple physics process application with the relevant effects to simulate the Tevatron.
- Each physics process model has been independently validated.
- We have used the application to simulate a real world operational issue and support a parameter change resulting in a real improvement in luminosity and reliability and safety.

Acknowledgements

Argonne Leadership Computing Facility

National Energy Research Scientific Computing Center